

Near-band-gap refractive index of GaSb

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Abstract

We have measured the refractive index of GaSb by ellipsometry for the wavelength region below band gap ranging from 1.75 to 2.5 μm . As far as we know, this is the first measurement for this wavelength region using this technique. There is a lack of agreement amongst the previous values reported in the literature for this material, where other techniques have been used. We describe the approach used here to obtain the refractive index from the ellipsometry parameters and then compare our results with the ones previously reported.

Keywords: Gallium antimonide; Refractive index; Ellipsometry

1. Introduction

Progress in epitaxial growth techniques has made possible the use of thin film structures grown on GaSb substrates in optoelectronic devices [1]. In designing such devices, a very important input parameter is the refractive index of the compounds involved. An accurate determination of the GaSb refractive index is important not only because its value may be directly needed but also because any inaccuracy would mislead the refractive index determination for thin films grown on GaSb substrates. In a survey of the literature on this subject we have found three reports of GaSb refractive index measurements in the transparency region ($\lambda \geq 1.72 \mu\text{m}$) [2–4]. In all these works a reflectivity-type technique was used, while in Ref. [3] another technique based on measurement of the minimum deviation angle for a GaSb prism was also employed. For unknown reasons there is a large dispersion in the values reported in these previous works.

In the present work we report measurements of the GaSb refractive index for the wavelength region below band gap ranging from 1.75 to 2.5 μm . We have used the ellipsometry technique and, as far as we know, this

is the only work where this technique is applied for this wavelength region. As pointed out by Aspnes [5], if appropriate optical elements are available, ellipsometry is a more powerful approach than reflectivity for determination of optical properties.

2. Experimental details

We have used a manual Rudolph null ellipsometer, model 436. A 150 W tungsten lamp was employed as light source. The output power of the ellipsometer optics was measured with a commercial liquid-nitrogen-cooled InAs detector² whose signal was integrated by a lock-in amplifier. The desired wavelengths were selected by interference filters placed in front of the detector window.

In this particular set-up the data are obtained by reading the angles at which one has to position the polarizer and analyser in order to null the electrical field reflected by the sample. From the null settings one can obtain the experimental ellipsometric angles, which are usually denoted Ψ and Δ [6]. In the next section we discuss how from these data one can obtain the optical

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² The use of a less noisy detector instead of the cooled PbS detector supplied by the manufacturer has proved to be essential for achieving the experimental resolution reported here.

constants. In order to increase the accuracy of the measurements, we used so-called “four-zone averaging” and the “method of swing”³.

We performed the measurements for wavelengths centred at 1.75, 2, 2.3 and 2.477 μm . We used filters of 100 nm bandwidth, except for the one centred at 2.477 μm which had a bandwidth of 70 nm.

3. Data analysis details

In order to obtain the optical constants from the experimental data Ψ and Δ , one has to assume a structure for the sample. We assumed here a three-media slab wherein the first medium is air, the second is a native oxide with unknown thickness d and refractive index n_{oxid} and the third is GaSb with refractive index n_{GaSb} . The back surface may be disregarded because it was intentionally roughened to prevent the refracted light from being back reflected. This allows one to consider the semiconductor as a semi-infinite medium. The reflection coefficient of the slab is [7]

$$r_{123} = \frac{r_{12} + r_{23} \exp(i\phi)}{1 + r_{12}r_{23} \exp(i\phi)} \quad (1)$$

In Eq. (1), r_{ij} is the Fresnel coefficient for the interface between media i and j and ϕ is the phase propagation for a round trip inside the oxide medium

$$\phi = \frac{4\pi d}{\lambda} [n_{\text{oxid}}^2 - \sin^2(\theta_{\text{inc}})]^{1/2} \quad (2)$$

where λ is the light wavelength and ϕ_{inc} is the incidence angle.

Typical values for the oxide thickness are about 100 Å and the refractive index is about 2. The resulting values for ϕ are small enough to allow one to approximate the coefficient r_{123} by considering a first-order expansion. With this approximation one has

$$r_{123} \approx r_{13} + i\delta r \approx r_{13} \exp\left(i \frac{\delta r}{r_{13}}\right) \quad (3)$$

where

$$\delta r = \frac{4\pi(1 - r_{12}^2)r_{23}}{(1 + r_{12}r_{23})} [n_{\text{oxid}}^2 - \sin^2(\theta_{\text{inc}})]^{1/2} \frac{d}{\lambda} \quad (4)$$

By the ellipsometry technique one measured Ψ and Δ , which are related to the reflection coefficients for p - and s -polarized light ($r^{(p)}$ and $r^{(s)}$) by

$$\rho = \tan \Psi \exp(i\Delta) = \frac{r^{(p)}}{r^{(s)}} \quad (5)$$

Defining the ellipsometry parameters for the ideal case where there is no oxide film as Ψ_0 and Δ_0 , one has from Eq. (5)

$$\rho_0 = \tan \Psi \exp(i\Delta_0) = \frac{r_{13}^{(p)}}{r_{13}^{(s)}} \quad (6)$$

For the particular case where there is no absorption, the refractive index is a real number and so is $r_{13}^{(p)}/r_{13}^{(s)}$. For this hypothetical case there would be no information in Δ_0 with a value of either 180° or 0° , depending on whether the incidence angle is smaller or larger than the Brewster angle. Eq. (3) implies that if $\delta r/r_{13} \ll 1$, the presence of the oxide film deviates Ψ from the ideal value Ψ_0 only by a second-order term in $\delta r^{(p)}/r_{13}^{(p)} - \delta r^{(s)}/r_{13}^{(s)}$. Up to first order one has

$$\Psi \approx \Psi_0 \quad (7)$$

$$\Delta \approx \Delta_0 + \frac{\delta r^{(p)}}{r_{13}^{(p)}} - \frac{\delta r^{(s)}}{r_{13}^{(s)}} \quad (8)$$

The knowledge of Ψ_0 allows one to use Eq. (6) instead of Eq. (5) and obtain the refractive index of the substrate independently of any knowledge of d and n_{oxid} . An analytical expression for n_{sub} in terms of ρ_0 can be obtained, resulting in [8]

$$n_{\text{sub}} = \sin(\theta_{\text{inc}}) \left[1 + \left(\frac{1 - \rho_0}{1 + \rho_0} \right)^2 \tan^2(\theta_{\text{inc}}) \right]^{1/2} \quad (9)$$

The value of n_{sub} obtained from Eq. (9) can then be used in Eq. (8) to obtain information on the oxide and confirm the original assumption regarding its thickness.

4. GaSb refractive index

In Table 1 we present the results for a p-type and an n-type sample. The nominal carrier density values are 1.5×10^{15} and $4.6 \times 10^{17} \text{ cm}^{-3}$ respectively at room temperature. These results are also presented in graphical form in Fig. 1. One can see that below the band gap the index values for the n-type material are slightly smaller than the corresponding values for the p-type substrate. This is expected, because band filling in the conduction band increases the average gap and hence decreases the dielectric constant. This effect is not relevant for the p-type material, because the hole density is two orders of magnitude smaller, besides the density of states being higher in the valence band.

A usual procedure to obtain an empirical parametrization of the refractive index dispersion is to employ the so-called single-oscillator model [9]. This model

Table 1
Refractive indices for p-type and n-type substrates

Wavelength	P-type substrate index	N-type substrate index
1.75	3.968 ± 0.003	3.969 ± 0.003
2.0	3.886 ± 0.003	3.880 ± 0.003
2.3	3.853 ± 0.003	3.843 ± 0.003
2.477	3.839 ± 0.003	3.829 ± 0.003

³ The method of swing is described in Ref. [6], p. 386; four-zone averaging is discussed on p. 210.

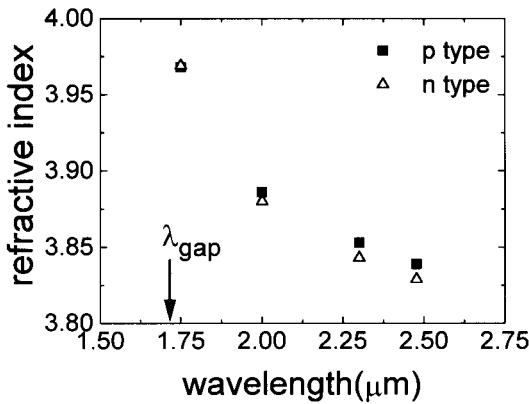


Fig. 1. Plot of refractive index vs. wavelength for p-doped and n-doped GaSb.

assumes that the small frequency limit of the dielectric constant ($\epsilon = n^2$) can be described by

$$\epsilon(\omega) = 1 + \frac{\omega_o \omega_d}{\omega_o^2 - \omega^2}$$

where ω_o and ω_d are two empirical parameters. This trend can be better visualized by plotting $[\epsilon(\omega) - 1]^{-1}$ vs. ω^2 as in Fig. 2.

One can see that the slope of the curve tends to a straight line as the frequency decreases. We cannot obtain reliable values for the parameters ω_o and ω_d from this curve, because the frequency range covered here corresponds to 0.7–0.98 of the band-to-band transition frequency and does not probe the low frequency region far enough.

5. Oxide index and thickness

As discussed in Section 3, one can use Eq. (8) to evaluate the oxide thickness and its refractive index to confirm that the data are consistent with the original

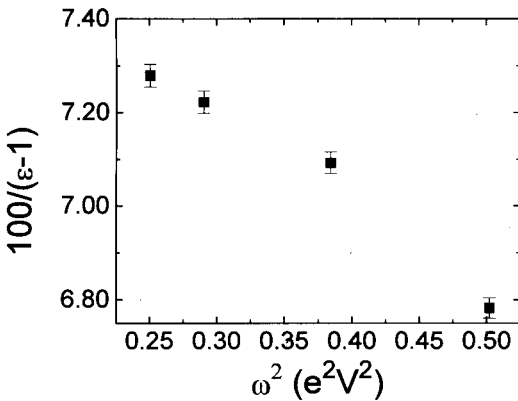


Fig. 2. Plot of dielectric constant factor $100/(\epsilon - 1)$ vs. ω^2 for p-doped GaSb.

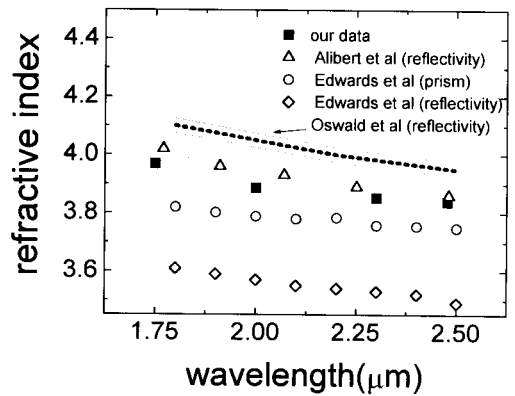


Fig. 3. Comparison of refractive index vs. wavelength for p-doped GaSb with previously published results.

assumption that the oxide is approximately 100 Å thick. Since both the refractive index and the thickness are unknown, one needs the values of Δ at two different angles to obtain the solution. The values for $\Delta - \Delta_0$ at 2.3 μm were found to be 0.8° and 1.4° at angles of 45° and 50° respectively. Eq. (8) yields $n_{\text{oxid}} \approx 2$ and $d \approx 70$ Å.

6. Discussion

In Fig. 3 we present our data for the p-type sample and compare them with the results of Alibert et al. [4] ($p \approx 10^{17} \text{ cm}^{-3}$), Oswald and Shade [2] ($p \approx 10^{17} \text{ cm}^{-3}$) and Edwards and Hayne [3] ($p \approx 10^{17} \text{ cm}^{-3}$). The data of Oswald and Shade are available in a very condensed graphical form, which prevents us from retrieving the values with their original resolution. The dotted lines indicate the margin of error in retrieving the original data.

One can see that there is a large dispersion in these results. The reason for this disagreement is not clear to us. One possible source for it could be the effect of the handling of the oxide layer on the measurements. In all these references there is no mention of whether or how the oxide layer was taken into account in processing the raw data.

As we stated before, an inaccurate value for the refractive index of GaSb would mislead the determination of the index for any thin film grown on GaSb substrates. This is a timely matter, because efforts are currently being made to develop GaInAsSB/GaAlAsSb/GaSb double-heterojunction lasers emitting in the 2.0 μm region. The index step required to waveguide the radiation is a very important input for designing and evaluating the performance of such lasers [10]. For this purpose a precise determination of the refractive indices of the compounds involved in the laser structure is necessary.

Acknowledgements

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